Some Studies on Uncertainty and Disturbance Estimation based Techniques for Control System Applications

Ph.D. Workplan

Submitted to

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1) A brief resume of proposed problem

Many physical plants in real world are not only nonlinear and time-varying but also highly uncertain. Accurate mathematical models of physical plants are usually not available in industrial control. Various dynamics like uncertainties, non-linearities, unknown disturbances, time delays, cross coupling effects and external disturbances are present in the systems This creates a challenge for control practitioners to design a controller for plants with unknown dynamics subject to unknown disturbances. For continuously modulated control, a feedback controller is used to automatic control a process or operation. The desired characteristics of feedback control systems is robustness in presence of uncertainties and disturbances in terms of stability and performance. In order to achieve robustness various control schemes are used.

Control strategies are important to guarantee that industrial processes are operating within safety bounds and operating conditions to yield better performance. The external disturbance acting on systems is a major concern, which cannot be directly measured or is too expensive to measure. The method to deal with this problem is to estimate the disturbance (or the influence of the disturbance) from measurable variables and then, generate control action based on the disturbance estimate, to compensate for the influence of the disturbance. The mathematical model of the process by which a state-vector is estimated from the measured output and the known input is called an Observer or state estimator. A controller which generates the control input to the plant based on the estimated state-vector is called a Compensator. There are various disturbance estimation and compensation techniques like Disturbance Observer, Extended State Observer, Unknown Input Observer, Uncertainty and Disturbance Estimator(UDE) etc.[1].

There are several techniques reported for uncertainty estimation like Time delay control (TDC) under the assumption of accessibility to all the state variables and estimates of their delayed derivatives, the TDC is characterized by a simple estimation technique that evaluates a function representing the effect of uncertainties. [3] This is accomplished using time delay. The time delay rings difficulties into system analysis and causes some drawbacks like oscillations in the control signal and the need of measuring the derivative of the past states.

Zhong and Rees proposed an alternative control strategy to obtain similar performance to TDC, which used an assumption in the frequency domain. This controller is called as UDE[4]. The UDE is designed to estimate the plant uncertainties as well as external disturbances without the knowledge of the bounds on the uncertainties. UDE is a control strategy that cancels model uncertainty and external disturbances, allowing for the straightforward control of complex nonlinear, time delayed systems with disturbances. Delay is not introduced in the system. There is no need for measuring the derivative of the states and no oscillation in the control signal, Hence less control efforts are required to counter disturbances and uncertainty. Stability analysis of UDE based control system is easy as compared to others. UDE only uses the control signal and the states to observe the uncertainties and the unpredictable disturbances The control algorithm based on the UDE is a robust control strategy and has received wide attention in recent years due to its simple structure and wide applicability[5]-[14].

Considering all the merits and applications of UDE based control design. It is proposed to design control techniques and perform numerical simulation for control of Single input single output (SISO) and Multi input multi output(MIMO) systems like two-link robotic manipulator, Flexible joint, Two-input–two-output (TITO) interactive processes, Quadruple tank system, Continuous Stirred Tank Reactor (CSTR) control etc. In order to investigate the effectiveness of UDE based control strategy an experimentation and

real time implementation for control of SISO and MIMO systems like flexible joint, two-link robotic manipulator, d. c. servomotor position and velocity control, inverted Pendulum, interactive processes etc. can be considered.

2) Introduction to proposed research topic.

Uncertainty and Disturbance Estimator (UDE): The control algorithm based on the UDE is considered as an efficient control strategy that has attracted much attention recently. Uncertainty and disturbance estimator is a control strategy that cancels model uncertainty and external disturbances. The basic premise behind UDE is to estimate model uncertainty and external disturbances by passing it through a low-pass filter of appropriate bandwidth. The resulting signal can cancel the real uncertainty in close-loop with the system dynamics. UDE based control has more potential for better performance than TDC since it provides an additional compensation for canceling system nonlinearities and undesired dynamics. The UDE only uses the control signal and the states to observe the uncertainties and the unpredictable disturbances The control algorithm based on the UDE is a robust control strategy and has received wide attention due to its simple structure and wide applicability.

UDE-based controllers include three design freedoms: a reference model, an error feedback gain and a filter. The selection of the reference model is very clear, researchers have provided brief guidelines in the literature for the selection of the error feedback gain and the filter. For example, the filter is often chosen as an Low Pass Filter to allow all the frequency components of the disturbance and uncertainty signal to pass and the error feedback gain normally chosen as 0. Q.C. Zhong et. al. proposed two-degree-of-freedom nature of UDE-based controllers where The set-point tracking response is determined by the reference model, whereas the disturbance response and robustness are determined by the error feedback gain and the filter introduced to estimate the uncertainty and disturbances.

In uncertain nonlinear multiple input multiple-output (MIMO) systems, designing a controller is a challenging problem, due to severe nonlinearities as well as significant cross coupling between their control channels in open-loop dynamics and also by external disturbances and uncertainties in plant parameters. In such a situation, the centralized controllers may not provide satisfactory control performance due to high coupling among the control loops. The decoupled model following control shall be proposed by considering plant parameters as an unknown components as well as the effect of input coupling, external disturbances, parameter variations and input nonlinearity as a lumped uncertainty which is estimated by using techniques like UDE. It makes the system output robust against coupling nature, external disturbances and parameter variations in MIMO system[11].

The simplicity of control design supplemented by estimation capability of UDE is an attractive approach. The applicability of designed control to a wide range of systems like mechanical systems, robotics, electric systems etc. leads the to believe that uncertainty estimation i e. UDE based control along with sliding mode control techniques shall be a major topic of interest in robust control.

In flexible joint robotic systems while designing the manipulator the problem of joint flexibility has received considerable attention as the major source of compliance. This joint flexibility typically arises due to gear elasticity, shaft windup etc. and is important in the derivation of control law. Perhaps it is more critical to address the joint flexibility when dealing with force control problems, than it is for pure position control. Joint flexibility must be taken into account in both modeling and control in order to achieve better tracking performance, for practical applications. unwanted oscillations due to joint flexibility, imposes bandwidth limitations on all algorithm designs; based on rigid robots and may create stability problems for feedback controls that neglect joint flexibility. Control of flexible joint has been an important research topic and received considerable attention.

Control of robotic manipulators is an area of active research, owing to its highly coupled nonlinear dynamics, it offers a challenging task for high performance control system design. The task gets further compounded when the system is subjected to various model uncertainties and unmeasurable external disturbances. The Feedback Linearization (FL) is one of the most prominent approaches in nonlinear control systems design. One of the advantages offered by the FL approach is that it provides a systematic framework for designing controllers for nonlinear systems. It offers asymptotic tracking of the reference trajectory only when the models are known exactly but modeling uncertainties are always present, there is a need to robustify the FL-UDE-based control designs[5]-[8].

Control of large-scale industrial processes becomes challenging due to several inherent characteristics and it is difficult to theoretically build an accurate model because of the process complexity. Most of the processes are always suffering from diverse disturbances from various sources, requiring strong disturbance rejection ability. The *time delay* characteristics widely exist in process control, in the form of real transport delay. The UDE based control has capability which can be demonstrated effectively for robustness enhancement and disturbance rejection in such processes as compared to conventional strategies. Many chemical processes, such as a chain of evaporators, are of very high order,
whose states need to be measurable for the UDE algorithm. However, most of the internal states are difficult to measure. Therefore an approximate FOPDT model shall be used, based on which the UDE is to be designed.[16,18]

In order to extend the applicability of UDE to the industrial processes with time delay a modified UDE (MUDE) control approach by dividing the original control law into three parts and revising them individually: i) An *artificial delay* is incorporated to make the input signals of UDE synchronized ii) a virtual process is designed to derive feed-forward control law rather than the original state feedback form, making the design of tracking and disturbance rejection independent iii) the original error feedback law is revised by borrowing the output of the virtual plant proposed in the literature. This MUDE can be applied and verified on two-input–two-output (TITO) interactive processes, Quadruple tank system, CSTR, heat exchanger etc.

3) Review of literature and development in the relevant subject

The design and development of robust control strategies like UDE in presence of uncertainty and disturbances are reviewed in context of following aspects.

- Disturbance estimators, compensators and controllers
- UDE control law and UDE Based Control design.
- UDE and extended techniques for control of SISO and MIMO systems
- Recent work on UDE and opportunities.

As the practical systems are usually affected by plant uncertainties, unmeasurable and unpredictable external disturbances. In order to achieve robustness there have been several conventional robust control approaches such as high gain control, adaptive control, sliding mode control etc. One of the approach that has been explored widely for designing robust controllers for uncertain systems is based on the concept of uncertainty and disturbance estimation and compensation. The idea is to estimate the effect of uncertainties and disturbances acting on the system and compensate the same by augmenting the controller designed for nominal system through a new class of control philosophies called as disturbance observer and related techniques. It has shown as a powerful paradigm to produce satisfactory performance. Various disturbance estimators like Disturbance Observer(DO), Unknown Input Observer (UIO), Perturbation Observer (POB),

Extended State Observer (ESO), Uncertainty and Disturbance Estimator(UDE)[1][2]. Estimators are reviewed in terms of applicable dynamic structure of plant. Hence the uncertainty and disturbance compensation strategy and design consideration scale down trade off between performance and stability of system which improves robustness.

The concept of TDC proposed by Youcef Toumi and Ito[13]. Addressing certain drawbacks associated with it, a novel Uncertainty and Disturbance Estimator (UDE) technique is proposed in Zhong and Rees [4] wherein the effect of plant uncertainties and external disturbances is estimated by employing an appropriate filter. Since then, various theoretical and applied results of UDE based control strategies have appeared in literature. For example, in Zhong et al. have brought out the two-degree-of freedom nature of the UDE based controllers and it is shown that, in addition to the known advantages over the TDC, the UDE-based control outperforms TDC under the same operational conditions[5]. The authors Talole and Phadke have used UDE in addressing the issues of requirement of knowledge of uncertainty bound and chattering in sliding mode control. The stability of system has proved through the existence of a sliding surface[6]. The UDE based robust control designs for uncertain linear and nonlinear systems with state delays are studied in Kuperman and Zhong where stability is proved by the small-gain theorem applied to the characteristic polynomial of the closed-loop system[7]. Results on extension of the UDE technique for uncertain nonlinear systems can be found in Deshpande and Phadke[8].

The UDE has been applied to many linear and non linear systems, several applications of the UDE based controllers have also been reported in the literature. The non linear systems are linearised using a feedback linearization (FL) and the observer based control law is made implementable using ESO, is proposed for the trajectory tracking control of a flexible joint robotic system in[9,10]. Shendge and Patre applied a SMC-based UDE controller to a linearised load frequency control, concluding that the proposed methodology offers excellent tracking capabilities for changing all parameter from 50% to 98% from their nominal values[11]. Dadekar et al. proposed full-order model following sliding mode control based on UDE technique and implemented on MIMO system. The effectiveness of control scheme is demonstrated through numerical simulation of two-link manipulator[14]. Londhe et al. Implemented UDE for controlling steering and diving planes based sliding mode control as single input single output controllers for horizontal and vertical plane dynamics of an Autonomous Underwater Vehicle system for compensating the uncertainties in the hydrodynamic parameters of the vehicle and rejecting unpredictable disturbances due to ocean currents[15]. Aditi Bhatt et. al. designed backstepping control robustified by UDE for ship steering autopilot which offers uniform performance in the presence of uncertainties and disturbances. Jiguo Dai. et. al. proposed UDE-based controller for nonlinear systems with mismatched uncertainties and disturbances by integrating the UDE-based control and the conventional backstepping scheme. It is proved with numerical and experimental studies, that the backstepping approach is promising to handle the mismatched uncertainties along with UDE.[19,20]

The simplicity of control design boosted by estimation capability of methods like UDE is an attractive approach. The applicability of designed control to a wide range of systems and efficacy on robustness enhancement and disturbance rejection is demonstrated and validated in literature.

4) Objectives of the research and proposed hypothesis.

1. Study of various Disturbance estimation and compensation techniques.
2. Study of UDE techniques and control Laws.
3. Implementation of UDE based control on SISO and MIMO systems like DC servomotor, Two-link robotic manipulator, Flexible joint, Interactive processes, Quadruple tank system, CSTR etc.

4. Implementation of UDE and modified UDE based control schemes for Nonlinear systems with mismatched uncertainties and disturbances.
5. Numerical simulation and Experimental validation
6. Investigation and real time implementation.

5) Methodology to be used and adopted

The following methodology is used to meet the objective and according the work is divided into distinct phases:

- Study and design uncertainty and disturbance estimation methods like UDE to counter the effects of model uncertainties and external unpredictable disturbances in SISO and MIMO system.
- Effects of uncertainties and disturbances are nullified by using the estimate and proper filter selection. If required then SMC, Backstepping, Multi time scale feedback control or similar strategy shall be used in combination with UDE to fulfill the objective.
- Control schemes are validated by simulation in Matlab/Simulink environment as well as by conducting experiments on a laboratory setup.
- Comparative study, stability analysis and performance evaluation.

6) Importance of the study

Practical systems like various chemical processes, nuclear reactors, electrical, hydraulic and mechanical systems are generally modelled as nonlinear systems with time delay. Disturbances and uncertainties widely exist in all industrial systems and bring adverse effects on performance and stability of control systems. In the applications, either the system parameters are poorly known or large unpredictable parameter variations and unexpected disturbances exists. In such circumstances it is economically desirable to operate the chemical processes, robotic systems, nuclear power reactor etc. at close to the desired operating levels or designed power level. Many benchmark controllers like PID, SMC etc. are used traditionally. But if uncertainties in the parameters increases, the performance of PID controller becomes poorer. It indicates that the PID controller provides a limited stability range under the effect of lumped uncertainty like trajectory tracking controls, frequent load changes. Robust strategy like SMC gives an acceptable control performance but at the cost of chattering phenomenon in the control signal with the limitation that the upper bound on uncertainty must be known.

In this context to deal with effect model uncertainty and disturbance, it is required to estimate the disturbance or its influence from measurable variables and then, generate control action based on the estimate to compensate it. There are many disturbance estimation and compensation techniques in literature. The objective of this study is to propose most simple and generalized control design strategy to counter the dynamics based on estimation. A simpler observer and compensation technique UDE is used to deal mentioned dynamics in the various applications discussed.

The UDE controller is divided into the reference model to generate a desired trajectory, a local positive-feedback loop via the low-pass filter (behaving like a PI controller), The polynomial formed with feedback gain for error tracking, which form the derivative effect. The UDE controller uses more derivative information than the common PID controller, and, hence, UDE-based control has the potential to obtain better performances than the common PID controller[4].

UDE is a control strategy that cancels model uncertainty and external disturbances, allowing for the straightforward control of complex nonlinear, time delayed systems subject to disturbances. The UDE strategy has been applied successfully in the extension of control strategies initially designed for systems

without disturbances (input output linearization, feedback linearization, sliding mode control). The main idea behind the controller is that a filter of appropriate bandwidth can estimate an unknown signal accurately enough, so the estimation can be utilized in the control design to cancel system uncertainties and external disturbances. The proposed work will add new methodology and characteristics of UDE which can be applied to linear systems with fast varying disturbances, nonlinear systems like CSTR and multi-variable systems which has interactions, coupling effects, robotic manipulators to obtain desired performance. The control design will be validated by simulation in Matlab/Simulink environment as well as by conducting experiments on a laboratory setup.

7) Proposed work plan- with a tentative chapter scheme

- Chapter 1: Introduction and Literature Survey
- Chapter 2: UDE based control law
- Chapter 3: UDE control law for SISO and MIMO systems
- Chapter 4: Investigation of UDE based control strategies for linear, non linear benchmark models
- Chapter 5: Investigation of UDE based control strategies for Process control applications
- Chapter 6: Investigation of UDE based control strategies for Mechanical/Robotic Systems with mismatched uncertainties.
- Chapter 7: Comparative study and stability analysis
- Chapter 8: Conclusion

8) Year wise plan of work and targets to be achieved

Sr. No.	Year 1	Year 2	Year 3
1	Literature Survey of Uncertainty and disturbance estimator(UDE) and study of key parameters in UDE implementation like filter selection, stability issue, applications etc.	Study and development of UDE based control strategies for linear, non linear benchmark models and systems eg. D.C. servomotor positioning system, inverted pendulum, flexible joint, ball and beam system etc.	Study and Investigation of UDE based control strategies for linear and non linear model of Robotic systems.
2	Study and Design of UDE based control law and different approaches for various applications in literature.	Design and Investigation of UDE based control strategies for process control applications like CSTR, Quadruple tank MIMO systems etc.	Comparative study, stability analysis, accuracy, robustness and efficacy of proposed control strategies.
3	Implementation of UDE control law on SISO and MIMO systems in the literature using MATLAB and Simulink.	Experimentation and real time implementation of UDE based control strategies.	Preparation of Report

9) Expected outcome

1. Simulation of different UDE based control strategies in Literature.
2. Implementation of UDE based control strategies for linear and non linear benchmark models.
3. Investigation of UDE based control strategies for process control applications like CSTR, Quadruple tank MIMO systems.
4. Investigation of UDE based control strategies for linear and non linear model of Robotic systems.
5. Comparison of robustness and effectiveness of the proposed control strategy.

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